AIAA SPACE 2009 Conference & Exposition
14 - 17 September 2009, Pasadena, California

AIAA 2009-6540

Value-Centric Design Methodologies for Fractionated Spacecraft: Progress Summary from Phase 1 of the DARPA System F6 Program[1]

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One of the most ambitious efforts in value-centric design of a military aerospace system undertaken to date has been the parallel development by four performer teams, headlined by major space industry primes, of design tools for fractionated space architectures under DARPA's System F6 program. The goal of the System F6 program is to replace traditional, highly-integrated, monolithic satellites with wirelessly-networked clusters of heterogeneous modules incorporating the various payload and infrastructure functions. Such fractionated architectures can deliver a comparable or greater mission capability than monolithic satellites, but with significantly enhanced flexibility and robustness. In order to design an optimal fractionated architecture, the potential cost penalties due to the overhead of such a design must be balanced against the value enhancement due to improved flexibility and robustness.

The first, preliminary design phase of the System F6 program, simultaneously awarded to four competing industry teams led by Boeing, Lockheed Martin, Northrop Grumman, and Orbital Sciences, commenced in February 2008 and included a significant effort for the development, validation, and demonstration of a Value-Centric Design methodology and associated tool suite that can support the design of optimized fractionated satellite systems based on a net lifecycle value metric and a probabilistic distribution thereof. This phase concluded in February 2009 and the Value-Centric Design methodology development to date is documented in a series of papers by the industry performer teams. This paper, from the System F6 Program Office, summarizes the overarching objectives of the Value-Centric Design effort, details and rationalizes the requirements for the methodology, discusses the relationship between Value-Centric Design and the traditional industry-standard systems engineering process, and fills any gaps in the performers' own presentations of their efforts, tools, and results.

I. Introduction

THE DARPA F6 Program* is an exploration and demonstration of fractionated spacecraft, where a wirelessly linked, free-flying cluster of spacecraft acts as a single system. In the simplest and most obvious instances of

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Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **SEP 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Value-Centric Design Methodologies for Fractionated Spacecraft: Progress Summary from Phase 1 of the DARPA System F6 Program1**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Defense Advanced Research Projects Agency,Arlington,VA,22203**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
AIAA SPACE 2009 Conference & Exposition, 14-17 Sep 2009, Pasadena, CA

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

fractionation, a cluster could functionally replace a single traditional monolithic satellite. Perhaps an earth-observing weather satellite is replaced by an imaging module (a “module” being synonymous with an individual spacecraft), a computation and data handling module, and a communications module, all physically separate but connected by wireless data links. More advanced implementations of fractionation would be capable of functionality beyond the reach of a single traditional spacecraft (by creating sparse apertures, for example). Such alternative capability, though very possible, is not the primary motivation for fractionation. As will be discussed below, breaking out of the conceptual bond that ties a space system to a physical spacecraft opens the door for more flexible, robust, responsive, and ultimately more cost effective space systems.

The F6 Program plans to build and fly a fractionated spacecraft system to demonstrate the concept and the potential value of fractionation, enabling rapid transition of this technology to existing needs. Phase 1 of the program, completed in February, 2009, funded four performer teams to perform conceptual design and much of the preliminary design for different fractionated spacecraft systems. Boeing, Lockheed Martin, Northrop Grumman, and Orbital Sciences each led one of the teams.

These teams were provided with very few specific mission requirements. Instead performance objectives—applicable to a wide variety of space missions and stakeholders—served as the driving basis of the architectural approach . The teams then chose reference missions on their own and applied a novel design approach called Value-Centric Design , which bases system engineering trade decisions on the net present value (NPV) and the variance of NPV for potential architectural solutions.

Each of the performer teams has published their approach to and methodology for Value-Centric Design.[1,2,3,4] This paper will summarize the lessons learned by the performers and add the perspective of the government team.

A. Key Concepts from Previous Work

We have written before on Value-Centric Design.[5,6,7,8] For convenience, we will recapitulate here some of the key ideas from those earlier papers.

1. Requirements, Capability, and Cost

A focus on achieving capabilities embodied in requirements while minimizing cost has, under the influence of technical and programmatic uncertainty, led to ever more complex spacecraft with higher and higher cost, a “cost-complexity death spiral.”[5] Decision makers respond to increased marginal cost by increasing the scale of spacecraft to maximize the overall capability/cost quotient, and increasing lifetime to minimize amortized annual costs.[9] Both trends increase capability, which drives further increases in scale and lifetime. The result is very large, very complex, and very costly monolithic spacecraft. Although much of the complexity in the design of monolithic spacecraft is intended to address uncertainty (for example, building in tolerance to space environments, with added margin) complexity itself makes systems more fragile, in the sense that they are vulnerable to many more unmodeled and unanticipated failure modes. Often such failures may be manifested as unplanned programmatic problems, not just operational failures in space.

Escape from the death spiral necessitates breaking out of the requirements-centric mindset. Value-Centric Design moves the focus away from just requirements toward finding a balance between cost and value, while also accounting for the variance of each in a given architecture. “Value is a measure—wholly apart from cost—that reflects the utility of a particular system to its owner or operator.”[8] Early work on Value-Centric Design developed the utility of flexibility and robustness, and responsiveness. These are all attributes that are of great concern to operators but tend to be underemphasized in requirements-driven programs because their value is realized in the face of uncertainties, such as program delays, funding reductions, launch failures, and on-orbit and on the ground events. Requirements are generally built around a scenario, or cast of scenarios, that envision what is *predicted* to happen. A system that is built to adapt to new (but not yet fully vetted) requirements, or is less likely to experience cost growth because of undesirable circumstances, is not afforded a quantifiable measure of goodness that can be compared with the less adaptable or less robust alternative. Value-Centric Design offers a toolset to allow such quantitative comparisons to be made.

2. Key Definitions

Value-Centric Design. The incorporation of value metrics, in particular net value and the variance in net value, into Systems Engineering.[8]

Flexibility. The ability of a system to change on demand. This incorporates scalability, evolvability, maintainability, and adaptability.[8]

Robustness. The intrinsic ability of a system to maintain functionality in response to unforeseen circumstances. This incorporates reliability, survivability, resistance to fragility, and fault tolerance.[8]

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[*] F6 is an acronym for Future Fast, Flexible, Fractionated, Free-Flying Spacecraft united by Information eXchange.

Responsive Space. The capability of space systems to respond rapidly to uncertainties, including technical uncertainty, environmental uncertainty, launch uncertainty, demand uncertainty, requirements uncertainty and funding uncertainty.[6]

3. Risk Management

Value-Centric Design fundamentally improves the systems engineering risk management process by allowing it to become entirely quantitative. Rather than minimizing risk, Value-Centric Design will locate a Pareto frontier of maximized risk-adjusted net values for a collection of possible investments. In other words, for a given cost, it will show the architecture with the maximum net present value. Likewise, for each architectural choice, Value-Centric Design will also inform the decision maker of the expected variance in value and cost, based on the forecast uncertainty in outcomes for key life cycle events. Risk mitigation is no longer a process divorced from the system design trade process. Instead, mitigation strategies are selected to trade net value against reductions in the variance of net value.[8]

4. Acquisition

With Value-Based Acquisition, acquisition decisions maximize net value for a given cost. Previous attempts at Value-Based Acquisition have foundered on the incommensurability of derived performance parameters such as flexibility, but Value-Centric Design promises to bring cost together with performance attributes and the less tangible derived attributes (to also include robustness, and responsiveness) in a system value model that links all the attributes to net value.

B. Overview

Section II below lays groundwork with a fundamental theoretical presentation of Value-Centric Design. Section III emphasizes applications of Value-Centric Design in the conceptual and preliminary design stages of system development, informed by experience from Phase 1 of F6. Section IV concentrates on risk management, reviewing results from the early F6 work and discussing where this might lead. Section V looks forward to the detailed design stage and suggests opportunities for improving the Systems Engineering process through application of Value-Centric Design. Section VI explores the topic of Value-Centric Acquisition, updating the perspective of our earlier papers. Section VII specifically addresses the F6 program and the impact that Value-Centric Design is making on the understanding and demonstration of fractionated spacecraft.

II. The Essence of Value-Centric Design

This section identifies the fundamentally distinctive aspects of Value-Centric Design, which are contrasted with the requirements-centric status quo.

A. Decisions and Outcomes

Value-Centric Design addresses the decision-making elements of design.[†] Decisions are evaluated prospectively, that is, according to their anticipated outcomes. In design, the outcome is the life cycle value and cost of the system, from manufacturing through operation until retirement. Under Value-Centric Design, design decisions strive to choose the desired system. The “desired” system is the one that the stakeholder desires, which necessitates a trade between value and cost, and the variance in each. A system value model estimates these value, cost, and variance metrics for a variety of architectures. The value model assigns a cost to a particular prospective system based on its anticipated attributes, including design cost, manufacturing cost, and launch cost. Value is determined based on payload performance capability, availability, and the user’s demand for service.

Design is inherently uncertain, even moreso in the conceptual and preliminary stages. If we knew exactly the outcome of each design choice, design would be nothing more than cranking out product definitions. Instead, designers face decisions with uncertain outcomes, so that the attributes of a prospective system design are best described by random variables. Therefore, in order to determine that one design alternative is better than another, we adhere to the logic of decision making under uncertainty, which tells us that the best design is one with the highest expected utility.[11] We can build this logic into the system value model. When we add in adjustments for value over time (cashflow discounting[12]), and subtraction of costs from benefits, the result is a system value model that produces a risk-adjusted expectation of net present value based on the probability distribution of design outcomes, described as a set of points in a Euclidean space of design attributes. We generally choose the design with the highest value, so defined.

[†] Hazelrigg[10] provides an excellent discussion of design as a decision-making process.

B. Value-Centric Design Compared with Requirements-Centric Design

In traditional requirements-driven systems engineering process,[‡] design choices are based on whether or not the outcome will meet the requirements. All designs that meet requirements are equally good. All designs that fail to meet requirements are equally bad. Uncertainty with respect to meeting requirements is managed by exception within the risk management process, even though such uncertainty is ubiquitous with regard to performance and cost requirements.

Value-Centric Design chooses the best design whether or not individual attributes exceed a threshold. If the best design is not good enough, the system is presumably not ready for development. Value-Centric Design acknowledges pervasive uncertainty and manages it, both to exploit opportunities (upside uncertainties) as well as avoiding less desirable prospects.

The next few sections will provide more detail and examples of Value-Centric Design in action.

III. Value Centric Conceptual and Preliminary Design

In Phase 1 of the F6 Program, all four performer teams developed Value-Centric Design Methodology (VCDM) processes to direct their system design choices in conceptual and preliminary design. In every case, the methodology distinguished design alternatives by attributes, typically including availability and always including life cycle cost, itself a collector embracing many subsidiary attributes (for example, manufacturing cost, launch cost, and cost of operation). A system value model was constructed to evaluate the designs based on the attributes. The methodologies took different approaches to utilizing these evaluations for design decisions.

A. Optimization

The broadest implementation of VCDM would be to parameterize the design, then use the system value model as an objective function to search the space of design parameters for the optimal design.[§] Automating the optimization process is not as easy as it sounds because the attributes of the point in design space must be assessed for every step in the search. However, some contractors developed system value models capable of projecting attributes from design parameters and optimizing the design. Even without this feature, optimization could be done with engineers in the loop estimating attributes.

Nevertheless, the performers did not use optimization as their basic design process. Instead, engineering judgement, backed by experience on conventional spacecraft, appeared to be the primary guide in searching for the overall system design.

B. Trade Studies

Another application of VCDM is to discriminate the results of system trade studies. Trade alternatives are constructed and the attributes of each alternative are quantified. The system value model is then used to score each alternative, and the highest scored alternative is selected.

Every performer team used VCDM for at least some of their system trade studies. For example, the number of modules in a fractionated cluster and the heterogeneity of the modules were used to construct trade studies which determined how many of what type of modules would be included in the eventual operational fractionated spacecraft. (Maciuca presents such an example in Fig. 21.[2])

Often other criteria entered into the decision in addition to risk-adjusted expectation of net present value. This indicated that perhaps not all the important attributes were present in the system value model.

[‡] The traditional systems engineering process is well described by the INCOSE[13] or NASA[14] Systems Engineering Handbook. The US Department of Defense provides similar guidance in Chapter 4 of the Defense Acquisition Guidebook, an online dynamic publication (see https://acc.dau.mil/dagch4).

[§] An objective function is the mathematical function that measures goodness during an optimization search, like a score that shows how well each point in the search is doing relative to the other. It is much like the childhood search game where the guide says, “You are getting hotter…No, now you are colder…Now hotter than ever!” The objective function is the thermometer that guides the search.

C. Rules of Thumb

DARPA asked the performers to apply their system value models to legacy systems and thereby try to gain some insight into the value of fractionation and the ways in which fractionation might be most effective. From these insights, the performers developed rules to serve as intuitive guides to designing the F6 system.

In retrospect, the legacy applications may have been too few to draw sound generalizations about fractionation. Also, the performers were under significant time and budget pressures, which perhaps limited the depth of the analyses. Finally, it might be that the final stages of enlightenment may often include a *déjà vu* feeling that you knew the hard sought truth all along. In any case, the rules which were developed felt like a mix of common sense, on the one hand, and unsupported overgeneralizations on the other.

We may need to wait until a few fractionated systems have been designed to a greater level of detail before we will be able to lay down some solid, useful design guidelines.

D. System Value Model

The major element in every performer's VCDM effort was the construction of a system value model. Each produced an elaborate life cycle model, some with automated design features built in, which could work from a set of design choices and environmental variables to measures of life cycle cost and performance. The environmental variables were varied probabilistically, allowing repeated model runs to generate Monte Carlo simulations of value prospects. Results were plotted as clouds of points or percentile boundaries on the spread of cases.

All the models were capable of illuminating trade studies by indicating the higher valued alternatives and providing underlying information about why the selected alternative was better. Phase 1 of F6 answered any doubts about the practicality of value models for use in the design of space systems.

E. Managing Uncertainty

The most powerful benefits of fractionation may be it its effectiveness in the face of uncertainty. Therefore, the work that the performer teams put into the probabilistic aspects of their system value models was essential to showing the true value of F6. Flexibility and robustness are terms that only make sense in an uncertain world, and we believe that responsive space is important because the environment is uncertain, so that we need to respond to sudden unexpected threats and opportunities.

Moreover, uncertainty is an essential element of system design, particularly in the conceptual and preliminary stages. If we really knew how a design would turn out, engineering would simply be a process of generating computer aided drawings and product definitions. A design is proposed, but the weight, power consumption, production cost, and lifetime are all uncertain. Traditionally, we have paid little attention to this uncertainty and assumed the design would realize its most likely weight, cost, performance, and so on. This is problematic, even on good days, because the distributions of these attributes tend to be skewed in a way that the expectations of weight, cost, power, and so on, are significantly worse than the most likely forecasts.

The performer value models addressed uncertainty by using Monte Carlo simulation to inject on-orbit failures, launch failures, shorter and longer component lifetimes, funding shortfalls, schedule delays, and all manner of other variations. The Monte Carlo process allows very unlikely events, and randomly distributed occurrences, such as Weibull-characterized component failures, to be incorporated into the value analysis in a straightforward and rigorously correct manner.

However, the use of Monte Carlo simulation creates some problems of its own. Optimization is difficult when using a Monte-Carlo-simulated objective function, for two reasons. First, Monte Carlo is by nature not repeatable. Two runs with the same inputs can never give precisely the same output, even with tens of thousands of trials, because the environmental variables are randomly generated. Optimization gradient search techniques and Newtonian searches rely on calculating derivatives, where the numerator is the difference in the value of two very similar inputs. When the value calculation includes a Monte Carlo simulation, most of the difference in value will be due to random variation in the simulation runs rather than to the slight difference in the inputs. (This can be avoided by preserving the randomized environmental variable settings for all ten thousand trials and reusing exactly the same settings for the second inputs. However, this becomes more of a designed experiment than a Monte Carlo simulation.) Second, tens of thousands of Monte Carlo trials can take a long time. When this process is embedded in the inner loop of an optimization, the combination can be so slow as to be quite inconvenient. We have become unaccustomed to employing design tools that require days to return an answer.

In the future, we may want to use Monte Carlo to characterize the impact of probabilistic inputs, but then develop a smoother and faster model, perhaps a response surface model, to use for design optimization.

F. Summary – Conceptual and Preliminary Design

System value model development was a large task for all the performers. The value models were not operational until late in Phase 1, after many of the design decisions were made. For that reason, the design work in Phase 1 of F6 was not as value-centric as it might have been.

The takeaway lesson is that we should have either had a study task prior to starting conceptual design in which the teams focused just on developing value models, or, more realistically, we should develop a much simpler and quicker approach to building small elegant value models for conceptual design work. When Value-Centric Design is embraced in the future by the acquisition community, value models should be developed in the Pre-Phase A portion of a program, not after. We have not yet worked out what descriptors like accuracy and realism mean in the context of a value model, but these models are clearly much different from models of physical processes like heat transfer or fluid dynamics. As we gain more understanding of the interaction of value models and the design process, perhaps we will get a better handle on how much detail is enough for a system value model.[¶]

IV. Value-Centric Risk Management

As we discussed in our last paper,[8] Value-Centric Design opens up a fundamentally new approach to risk management within system development. System value models that depict uncertainty and express value in dollars can quantify risks with clarity and precision that is lacking in the fever charts and waterfalls used to deal with risk today. Also, value models show the upside as well as the downside of program uncertainties, whereas traditional risk management focuses entirely on the downside, resulting in an overly conservative approach to advanced technology. [16] In Phase 1, the F6 performer teams began the development of systems engineering risk management strategies based on Value-Centric Design. This section will discuss lessons learned from that effort and look to the way ahead.

A. What is Risk?

In the systems engineering sub-discipline of risk management, risk is the possibility that something undesirable may occur. In contrast, the Value-Centric approach takes the view of economists, that a risk is an uncertainty that is relevant to a current decision or plan. The risk describes some future outcome that may turn out well or badly with some distribution of probabilities. On the good side are opportunities, or upside risks. On the bad side are the traditional downside risks.

A risk management system will need, at a minimum, to address technical risk, cost risk, and program risk.

1. Technical risk

A technical risk is a particular uncertainty in the attributes of the system under development, usually attached to a specific component, part, technology, or design that is the source of the uncertainty. As an example, a new satellite design may be unsure how the payload can be mounted on the deck of the satellite bus, and, depending on the mounting, the payload may interfere with a standard fairing that is planned for the launch vehicle. If, as the design progresses, the interference occurs, then a custom fairing must be developed or the bus will need to be modified.

An example of a technology-based technical risk might be a new polymer battery that promises to weigh less than legacy batteries. However, the lifetime of the new battery is uncertain. If testing reveals that the battery lifetime will significantly reduce the spacecraft life, the system may have lower value than if the heavier legacy battery is used. Saleh[17] provides useful data of the impact of technology readiness level, and implicit technology risk, on development schedule.

2. Cost risk

A cost risk is a specific situation that causes an uncertainty in development cost. Consider an earth-observing spacecraft development program. The image processing software will be developed by a firm in India. However, export approval for the software requirements specification is still pending. If approval is denied, a contractor in Los Angeles can do the software, but it will be much more expensive, and termination costs must be paid to the Indian firm. This is an example of a cost risk.

3. Program risk

Program risks includes risks of schedule delays, risks to meeting necessary milestones, or risks that arise from dependencies on other programs. For example, a spacecraft might be designed to be launched by a rocket that is still

[¶] For a more detailed discussion on the current state of value modeling in aerospace, see Collopy.[15]

under development. If the new launch system does not successfully enter service, the spacecraft will need to be redesigned, and a launch slot will need to be secured on another launcher.

To evaluate program risks, a system value model must be able to tie a monetary value to program delays. This is well within the capability of the value models developed by the F6 performers.

B. Risk and decision making

Risks can only be managed when there is a potential present or future action that can be taken by the program to address the uncertain outcome. For example, Congress may eliminate the budget for a spacecraft development program, but, unless there is some action available to the program team that would influence Congress, there is nothing the team can manage with regard to the risk. Another example might be the polymer battery case described above. What if the program commits to a two-battery power system, with one polymer battery and one legacy battery. The spacecraft is designed for the worst case performance of the polymer battery. The design decision is made and there is no turning back. This ceases to be a risk to be managed, because, even though the outcome is still uncertain, there is no longer a decision to be made. The future will simply play out. In another case, there is uncertainty whether the structure of a vehicle can carry necessary torque loads, so a brace is added to increase the load capacity. The decision is complete, and there is no longer a risk to manage.

Uncertainty is the essence of risk. Consider a program where schedule delays threaten a planned design review. When there is a 50% chance that the review will need to be delayed, this situation can be managed as a risk. Once there is a 95% chance the review will need to be delayed, there is little uncertainty left. It is time to reschedule the review and drop the issue from the risk management process.

In summary, a risk needs management when there is a present or future decision to be made in the face of uncertainty. Value-Centric Design can place a dollar value on the prospects that may occur, and aggregate these into an expectation of value for each alternative. A decision analysis can be performed to look at the impact of information on a future decision, such as the impact of results from a verification test. How likely is it that the test data will change the decision? Is it worthwhile to obtain more data before deciding?

C. Risk Management in Systems Engineering Today

In the status quo systems engineering process, a potential problem is identified as a risk, a mitigation plan is instituted, and the plan is described on a risk waterfall chart where every action reduces the expected loss (probability of failure times consequence of failure) of the risk until it can be colored green on a risk-assessment fever chart. While the trip down the waterfall may generate a sense of accomplishment, and even drama, it is hard to understand what this all really means. If a plan is in place such that, when it is complete, there will be little or no risk, then there is at present little or no risk, because the plan is in place. A "waterfall" chart can only be meaningful if it identifies certain future points where information will arrive, and the information is of a sort that can make the expected outcome better or worse. That is, there must be branches in the chart, and at each branch, some water should go downhill and some should go uphill. Management should be tracking the waterfall because there will be decisions to be made based on the new information.

To put it another way, how can a risk be yellow if, no matter what happens in the future, it will eventually be green. If we know it is going to be green in the future, then it is green now, since the color is nothing but a projection of future outcomes. If it is truly yellow today and may become green in the future, then the green prospect must be balanced by a red, or at least darker yellow, prospect to justify the "on balance" (or, technically, "expected value") rating of yellow.

With a more quantitative approach to measuring risk, we have the opportunity to implement a more meaningful risk management program that focuses program management on real decisions and the importance of obtaining information to inform those decisions.

D. More Work to Be Done

In Phase 1, the F6 performer teams explored the evaluation of risks such as launch failures using their system value models. Each team also executed a classic risk management process as part of Phase 1 systems engineering work. The performers have laid down plans to integrate Value-Centric Design and their risk management process during the next phase of F6.

V. Value-Centric Detailed Design

Looking forward, Phase 2 of the F6 program will extend Value-Centric Design to the detailed design phase, where it will be applied to the design of components of the fractionated spacecraft modules. How this is done will

be up to the performer, but some possibilities raised in previous work are distributed optimal design[18] and management with scoreboards.[19] These approaches were not introduced in Phase 1, and the government team will not be requiring them in Phase 2. They are discussed here only as illustrations of the possibilities inherent in the Value-Centric Design perspective.

A. Distributed Optimal Design

Optimal design literally means making the best system, and who would not want the best? And yet, although optimization is now widely used in conceptual design studies, very little optimization is done in the detailed design stage, when the system has been divided up into components, and the components are designed by independent teams. In part, the barrier has been the fear that components would be *suboptimized*, that is, improved from a perspective that conflicts with the overall system view, and therefore causes more hurt than help. Value-Centric Design offers the opportunity to create objective functions for each component that are consistent with the system value model. When design choices are made to maximize the objective function, optimal design is taking place. In this way, each component can be improved from a perspective that is deliberately consistent with the overall system view, so that suboptimization is no longer a danger.

Here is a boiled-down outline of how component objective functions can be derived from the system value model. System attributes like weight, cost, power consumption, and reliability are aggregate functions of component weights, costs, and so on. If the individual component attributes are perturbed, they will cause system attributes to change, and therefore will change system value. The induced change in system value divided by the amount of perturbation in the component attribute can be used as the coefficient of the attribute in the component objective function. By perturbing each component attribute, one at a time, an entire component objective function can be derived, as illustrated in Figure 1 where the linear objective function coefficients are placed in the "gradient" column. This process is very similar to sensitivity analysis.

If every component is designed to maximize its objective function, and the objective functions are all derived from a single system value model in the manner just described, the whole system is optimized. This is somewhat abstract, but is easier to grasp if the component objective functions are implemented in design scoreboards.

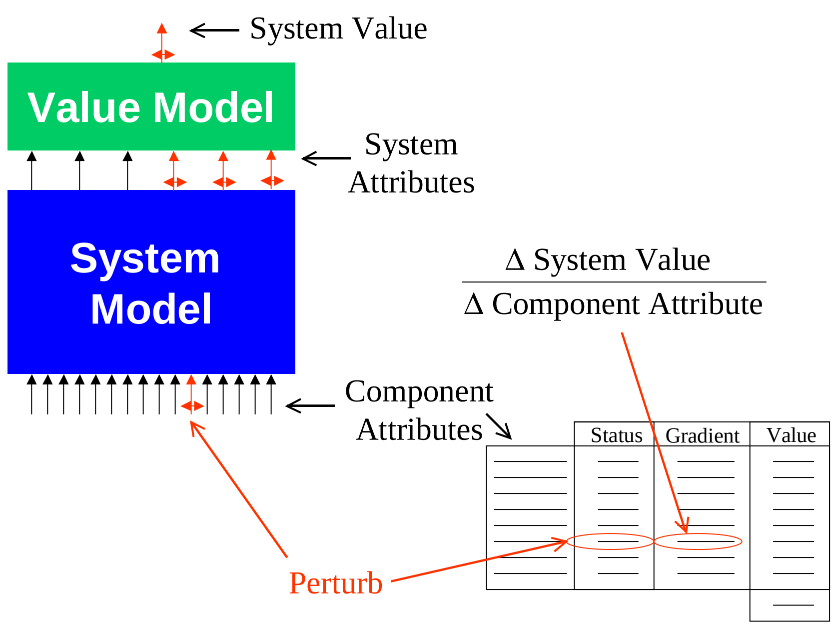

Figure 1. Deriving a component objective function by perturbing component attributes. *A single component attribute is changed. This causes system attributes to change which changes the system value. The ratio of the change in system value to the change in the component attribute becomes the coefficient of the component attribute in the component objective function, which is the inner product of the status column and the gradient column in the table.*

B. Design Scoreboards

Figure 2 shows a design scoreboard for a satellite bus. The scoreboard is merely a linear objective function laid out in table form. The left column lists the names of the component attributes which describe the bus. The status column shows the current estimate of each attribute. These attributes are the input to the objective function. The gradient column contains the coefficients of each attribute in the function. The value column is the product of the gradient and status, computed row by row. The Design Value, which is the output of the objective function, is the sum of the value column (and thus the inner product of the gradient and status columns).

The scoreboard is a guide for design decisions and optimization. If a team is considering an alternative design that reduces the mass, volume, and power consumption of their component while saving cost, that is an easy decision. The alternative is better because it is better in every way. But more common and more difficult design choices are when one option has lower mass and lower cost while the other option requires less power and volume and increases component reliability. Which is better? If the attributes of each option are plugged into the Status column in the design scoreboard and the Design Value is computed for each, the better option will show itself because it will have more design value.

The scoreboard is a natural format for trade studies. The study option with the greatest design value is the one that is preferred.[#] Systems engineers often employ trade factors in doing such studies. The gradient column in the scoreboard implicitly contains all the trade factors between the attributes. By the chain rule of differentiation, the trade factors are simply the ratios of the respective attributes' entries in the column.

C. Expanding the Notion of Design Optimization

When we hear the term "design optimization," we tend to think of elaborate software tools that perform automated design. However, consider a component design team working with a scoreboard, trying out design after design in an effort to improve the design value. The next design they choose to try will likely be very similar to the previous trials that have shown the most value.

This process is unequivocally an optimization search, where the scoreboard is the objective function. However, it is optimization by hand, or optimization with engineers in the loop. Like automated optimization, it is a search for the very best design. It differs from optimization driven by computerized algorithms because it is slower, and it is much more robust. The team of people will avoid embarrassingly bad alternatives that a software tool might settle on. And the humans can cope with very poorly structured design spaces that would bedevil an automated process.

It has been suggested that designing components to allocated requirements is the chief source of cost and schedule overruns that are endemic in large aerospace and defense development programs.[21] If this is true, the use of scoreboards to flow direction down to design teams is an alternative to allocated requirements that avoids the pitfalls that cause overruns. (This method is in fact a "guidance technology" in the nomenclature of Baldwin and

	Status		Gradient	Value
Mass	700	Kg	-30,000 $ / kg	-21.00 $ millions
Power Capacity	2,450	Watts	6,081 $ / Watt	14.90 $ millions
Propellant Consumption	40	g / day	-295,852 $ / (gm/day)	-11.83 $ millions
Volume	4,000,000	cu. cm.	-2.00 $ / cc	-8.00 $ millions
Manufacturing Costs	20,000,000	$	-1.00 $ / $	-20.00 $ millions
Development Costs	250,000,000	$	-0.02 $ / $	-5.02 $ millions
Reliability	24,750	hr MTBF	21.94 $ / hr MTBF	0.54 $ millions
			Design Value	-50.41 $ millions

Figure 2. Example Scoreboard for a Navigation Satellite Bus. *This component scoreboard was developed by the AIAA Value-Driven Design Program Committee in a workshop at Orbital Sciences Corp. in April, 2006.*[20] *It has been scaled and normalized to manufacturing cost for readability.*

[#] There are always considerations that cannot be captured in a scoreboard, some of which may be political or otherwise non-technical. These will play into the decision and may dictate the outcome. However, the scoreboard provides a good starting place for the technical side of a decision.

Clark.[22]) But the complete solution to reforming large system design will necessitate changes to the way large systems are acquired.

VI. Value-Centric Design in Acquisition

If Value-Centric Design were to take hold in mainstream weapon system development programs, it would need to be at least endorsed by, and more likely integrated into, the defense acquisition system. F6 is an aggressive technology development program in which contractors were asked to develop system value models as a research activity to see how they would approach the task. However, on a full development program, the government should develop the system value model as part of requirements generation.[**] After all, it is the government's value of the various attributes that should be encoded in the system value model, not the contractor's.

A. The Current State of Defense Acquisition

According to the GAO,[23] current weapon systems development programs are overrunning 42% in development cost and 25% in production cost, and are reaching initial operating capability, on average, 22 months behind schedule. These figures are not inconsistent with Norman Augustine's assessment of programs in the late 1970's and early 1980's,[24] which, at completion, were 52% over in combined development and acquisition cost and 33% behind in schedule. Augustine used only completed programs, while the large majority of the GAO's sample set are still in development, and will presumably continue to get later and more expensive, so it makes sense that Augustine's figures are higher.

We have observed[21] that the requirements allocation process naturally brings about cost growth and schedule delays of an order that is consistent with Augustine's observations. The effect occurs mainly because engineers who are asked to maximize the probability that a component will meet its allocated requirements will often find that the safest design is one that just barely meets most of the requirements. The result is a marginal system that needs several redesigns or major changes to achieve functionality. Every redesign increases system development time and cost, and most redesigns add to the unit production cost.

On the other hand, a design team assigned to maximize design value is driven to choose designs that far exceed the levels of typical allocated requirements. The result is a robust design that is functional or nearly functional on the first go-round. This avoids long iterative development schedules and the attendant cost growth.

B. Value-Based Acquisition

Carter and White[25] describe how Value-Centric Design would be integrated into the acquisition process. They call their concept *Value-Based Acquisition*, or VBA. To quote:

> The key to VBA at the program level is the development of a value model that embodies key system design features, such as weight, manufacturing cost, reliability, and the like, as well as key acquisition concerns, such as cost and schedule … Once a quantitative value model has been defined, it can become the basis for contracting. A program officer can offer a contract in which price is a function of value. The contract would specify the price that the government would be willing to pay for different levels of performance … Under a value-based contract, a contractor maximizes profit by including only those features whose value to the government exceeds their cost.

When a firm accepts a contract under which their profit is directly tied to a system value model evaluation of their current design, they will naturally adopt the value model to guide the design, since this is the route to maximizing profits.

The firm will also want their subcontractors to adopt Value-Centric Design, to enhance profitability and to offload risk onto the subcontractors. The prime contractor will be driven to place incentives in its subcontracts that directly parallel the incentives in the government's contract.

[**] During the Joint Advanced Strike Technology Program in 1994, a precursor to the Joint Strike Fighter development program, the government team ran a tiered set of simulations (campaign-wide, tactical, mission, etc.) and used the data to build response surfaces in attribute space, all in the name of requirements generation. These response surfaces contained most of the information necessary to build a system value model for the Joint Strike Fighter.

VII. Value-Centric Design Results in the DARPA F6 Program

We have described Value-Centric Design and discussed how it was used in Phase 1 of the F6 Program. We have projected ways in which Value-Centric Design may contribute to later phases of system development programs. In this section, we will relate how Value-Centric Design methods specifically contributed to the development of the F6 demonstration program and refinement of the fractionated spacecraft concept.

We discuss in particular the models and simulations developed during Phase 1 to estimate system value and the frameworks developed for design optimization. We then present the results of design studies on fractionated spacecraft, which were conducted using these tools.

A. System Value Models

Each of the F6 performer teams developed a system value model to estimate the risk-adjusted net present value of putative satellite configurations in order to search for the best application of fractionation. "Net" implies benefit minus cost, so it is natural to consider these models in three parts: Cost models, benefit models, and the estimation and evaluation of risk.

1. Cost Models

Highly sophisticated cost models have been available for a long time, particularly in the satellite industry.[26,27] However, the F6 teams developed models which have achieved new levels of complexity and power. Along with parametric estimators of component costs, the models employ discrete event simulators to account for program events, such as launch failures and development delays, and on-orbit component failures. Each of the performer teams incorporated probabilistic simulation into their cost models, so that the resulting cost estimates are not point estimates, but instead probability distributions of estimates. Probabilistic estimation is essential to cost accuracy (see Hazelrigg,[10] p. 270 ff.), so this is a positive feature.

The models included component-level manufacturing cost models, development cost models, launch cost estimation, and post-launch system operation cost models.

2. Benefit Models

While cost modeling is old hat, benefit modeling is more unique to the F6 program, and therefore could present a greater challenge. All of the performer teams anchored their benefit models on a common measure: the amount of time that the space system was up and operating, feeding data to the ground.

The Orbital Sciences team[4] developed a sophisticated model for pricing the data feed, based on market dynamics. To develop this model, they used the same logic and company resources that go into creating a business plan for a commercial satellite. The Lockheed Martin team[2] established a constant price per megabyte for the data feed. Boeing[1] based the price of data on a conservative estimate of system cost,[1] such that the system was ensured of attaining a reasonable profit margin.

The Northrop Grumman[3] team used Multi-Attribute Utility Theory[28] to estimate the value of attributes of the service provide by their satellite system. Each attribute was valued on a dimensionless utility scale, then the attribute utilities were merged into a single summary utility.

3. Risk Evaluation

The designers used Monte Carlo simulation to manifest the uncertainty in system designs and configurations. Risk was then quantified as the variance or standard deviation in overall cost and benefit. Lockheed Martin provided plots of the expected net present value of alternatives versus the standard deviation of net present value, which illustrate the risk return frontier of best options. Orbital plotted net present value versus cost, which allowed a quick visual assessment of the impact of budget constraints. The scatter of the cloud of Monte Carlo results indicates the amount of risk. Boeing plotted benefit versus cost, so that the benefit/cost ratio becomes the slope of a line between the design point and the origin. Again, scatter indicated risk. Boeing fit the points to a normal distribution to estimate 1σ, 2 σ, and 3 σ standard deviation intervals and plotted ellipses around the mean of the data points to roughly indicated the spread. Northrop Grumman plotted dimensionless utility versus cost.

We still have some work to do solidifying the concept of risk-adjusted net present value, which is a candidate for our summary evaluator of F6 designs. Boeing used the 3σ lower limit of benefit/cost ratio as risk adjusted measure. The other teams did not integrate risk, benefit, and cost into a single measure.

In some of the early work that led up to Value-Centric Design, Saleh[29] explored the application of real options theory, including the Black-Scholes equation, to quantify the impact of uncertain environmental factors on a space system that could respond to uncertainty in a flexible manner. Interestingly, although all the performer teams were aware of this approach, none employed either the real options value lattice or the Black-Scholes equation in their system value models. Instead, the discrete event simulators implicitly implemented something like the method that

Saleh describes as decision tree analysis, in which the program takes decisions based on events that have occurred and the probability of events that may occur. It may be that the Black-Scholes approximation is not as useful when the system is already represented by a fairly detailed discrete event simulation.

B. Optimization

Some of the performer teams incorporated their system value model into an automated value-centric design tool. These tools were made up of a design generator and an optimizer which used the system value model as the objective function.

1. Generator

Boeing parameterized the design space and generated a factorial set of designs spread around the space. Lockheed Martin used MIT's Generalized Information Network Analysis[30] tool to generate fractionated spacecraft configurations. The Orbital Sciences team employed Georgia Tech's GT-FAST automated design tool to generate satellite configurations and component designs.

2. Optimizer

Lockheed Martin used the MIT Space Lab's Time-Expanded Decision Network[31] optimization framework, which specifically addresses system flexibility and adaptability in a multi-level optimization. Orbital Sciences developed a custom optimizer, the PIVOT tool, described in Figure 1 of their paper.[4] Boeing's approach was to visually pick out the best design on a plot of risk-adjusted benefits and costs.

C. Value of Fractionation

The F6 Value-Centric Design tools are of interest in themselves, but the F6 Program is particularly focused on the results of applying these tools to spacecraft designs that use fractionation. While we may expect in the future to find systems that are only possible with fractionated architectures, Phase 1 of F6 began simply by looking at fractionated alternative configurations to existing or near term space systems. Therefore, the essence of these design studies was the exploration of the questions "Does fractionation provide a better design?" and "If so, what about fractionation makes the design better?" Through these studies, we have gained insight into what is important and useful about spacecraft fractionation.

1. Earlier Studies

Some early clues were provided by studies that led up to the F6 program. Saleh[29] studied on-orbit servicing, a strategy that shares an important feature with fractionation: when an operational spacecraft ceases to function, it can be brought back into operation without launching a full replacement satellite. Saleh concluded that on-orbit servicing can provide net value, but this will not be apparent in a deterministic comparative cost analysis. First, benefits must be estimated along with costs, because increased benefits of on-orbit servicing account for substantial value. Cost effectiveness analyses alone would not show the benefit of these novel strategies. Second, a probabilistic analysis is essential because much of the value of on-orbit servicing is derived from the flexibility it provides.

Mathieu and Weigel[32] directly examined the value of fractionation, focusing on two applications: a communication satellite system and a navigation satellite system. In both applications, two fractionated configurations showed significantly lower life cycle cost than a monolithic satellite. In the first low cost configuration, one module contained the payload and a second module contained communication, data handling, and computation functions, with wireless communications between the modules. The second low cost configuration was like the first except that communication was separated onto its own module, for a total of three modules. Several configurations with larger numbers of modules were predicted to have cost comparable to a traditional monolithic configuration, with lower cost if high unit volume manufacturing savings (steep learning curve) was achieved, but higher cost than the monolith if volume effects were not as strong. Meanwhile, all of the fractionated configurations delivered greater utility than the monolithic configurations, so in the end the net value of fractionation may be quite large depending on the equivalent monetary value of the utility measures.

2. Is Fractionation Better?

F6 Phase 1 performers reported studies showing benefits to fractionated spacecraft over traditional monolithic satellites, confirming the earlier analyses. The Boeing team showed that an eight module fractionated configuration had higher cost, but higher benefit, and a higher benefit/cost ratio.[1] The fractionated spacecraft also had much lower risk, indicated by a much tighter spread of cost and benefit estimates. The study notes that, while configurations with more modules (more highly fractionated) showed greater benefit/cost ratios, the really steep jumps in benefit/cost ratio occur going from a monolithic spacecraft to configurations with two or three modules.

Lockheed Martin found many fractionated configurations with 10% to 20% greater expected net present value than an equivalent monolithic satellite. All of these higher valued configurations used two or three modules—

configurations with more than three modules had less value than the monolith. About half of the higher valued configurations also had significantly lower risk than the monolith, where risk was measured as the standard deviation of value.

3. Why is Fractionation Better?

Perhaps more important than the absolute results about which configurations have higher value is the insight into what properties make good fractionated designs. How can the concept of fractionation best be exploited?

Mentioned already is a common finding that two or three module configurations show the most dramatic increase in value when functionally replacing a monolithic satellite design. However, this rule would not necessarily apply to fractional architectures for wholly new capabilities. Mathieu and Weigel[32] note that fractionation provides scalability, which implies that very high performance space systems might employ many, many modules.

Two of the performer teams noted the importance of component technology readiness level (TRL) to module configuration. The Boeing team found that isolating a low TRL (technologically immature) component on a module more or less by itself improved overall system value.[1] In a similar vein, Lockheed Martin discovered it is a good practice to put similar TRL components together on a module, that is, to segregate components by TRL among the modules.[2]

Perhaps most significantly, fractionated spacecraft show less uncertainty in value, that is, less risk, when faced with random environmental events and random changes in needs and requirements. These are precisely the benefits of robustness and flexibility that we were anticipating.

VIII. Conclusion

Phase 1 of the F6 Program was a challenging venture into the unexplored territory of fractionated spacecraft design. Through intense efforts from the four performer teams, a great deal was learned about fractionation, and a wealth of experience was accumulated in the new systems engineering processes of Value-Centric Design. Value-Centric Design was implemented by each of the teams, and it successfully contributed to the fractionated spacecraft designs which they developed. We can expect even better results from Value-Centric Design in the future as its methods, processes and tools become more mature.

In Phase 2, we will continue to develop and apply Value-Centric Design methodology. We will execute the detailed design of F6, which will introduce additional methodological challenges.

Some of the areas we expect to delve more deeply into are

- Risk management
- Value-based acquisition and subcontracting
- Dynamic project management
- Benefit assessment

We look forward to reporting the results at the end of Phase 2.

Acknowledgments

The authors would like to acknowledge the support of F6 government team members Naresh Shah, Roberta Ewart, Gregory Richardson, Jay Penn, and Joseph Betser for contributing to the development of the Value-Centric Design concept, as well as the four F6 performer teams. This work was funded by the Defense Advanced Research Projects Agency of the US Department of Defense.

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